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Morphological Characterization and Spatial Distribution of *Dactylopius opuntiae* (Hemiptera: Dactylopiidae) in Northwestern Libya

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التوصيف الظاهري والتوزيع المكاني لحشرة *Dactylopius opuntiae* رتبة: نصفية الاجنحة، فصيلة: Dactylopiidae في شمال غرب ليبيا

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Abstract:
This research investigates the cochineal insect *Dactylopius opuntiae* (Cockerell) (Hemiptera: Dactylopiidae), a newly recorded invasive pest in Libya. This study investigates on mapping the spatial distribution of this insect across municipalities in Al-Jafara region in northwestern Libya, which represents the primary infestation site in the country. In addition, the study aimed to identify the precise morphological and field characteristics of this species. The results confirm that *D. opuntiae* was the dominant species throughout all surveyed municipalities of Al-Jafara. Morphological identification was confirmed using diagnostic microscopic characters, particularly the distribution of Wide-Rimmed Pores (WRP). Heat maps reveal that insect density and infestation severity were highest in the northwestern municipalities and gradually declined toward the south and southeast. Infestation severity varied markedly among municipalities, ranging from severe to low levels, the highest infestation severity was recorded in Al-Maamoura (86.4%), followed by Al-Maya (80.9%). These findings indicate that the rapid and severe spread of this pest urgently requires an Integrated Pest Management (IPM) strategy combining mechanical, chemical, and biological control methods to reduce population levels, limit further spread, and achieve long-term suppression through sustainable biological control and resistant host varieties.

Keywords: *Dactylopius opuntiae*, Invasive pest, Spatial distribution, Heat maps, Al-Jafara region, Integrated Pest Management (IPM).

الملخص
اهتمت هذه الدراسة بتحديد شدة الاصابة بالحشرة القرمزية *Dactylopius opuntiae* (رتبة نصفية الاجنحة: فصيلة Dactylopiidae) لنبات التين الشوكي نوع *Opuntia ficus-indica*, وهي حشرة غازية تم تسجيلها حديثاً في ليبيا. ركزت هذه الدراسة على حساب شدة الإصابة بهذه الافة في مناطق بلديات منطقة الجفارة، ورصدت التوزيع المكاني لهذه

الحشرة عن طريق رسم الخريطة الحرارية التي بينت انتشارها في منطقة الدراسة، بالإضافة الي تحديد صفاتها الظاهرية والتشريحية والحقلية الدقيقة لتأكيد تصنيف نوعها. بينت النتائج ان النوع *D. opuntiae* كان هو النوع السائد في كل بلديات منطقة الجفارة، وقد تم تأكيد التصنيف باستخدام الصفات المجهرية التشخيصية وخاصة توزيع المسام ذات الحواف العريضة (WRP)، والاشواك مخروطية الشكل ذات القمة المسطحة او المقطوعة. بينت خرائط التوزيع المكاني ان اعلي كثافة وشدة للإصابة تركزت في البلديات الشمالية الغربية لمنطقة الجفارة، حيث سجلت اعلي نسبة إصابة في بلديتي المعمورة (86.9%)، والماية (80.9%)، ثم انخفضت شدة الإصابة تدريجيا في بلديات الجنوب والجنوب الشرقي للجفارة. توصي هذه الدراسة الي تطبيق سريع وفوري لاستراتيجية الإدارة المتكاملة للمكافحة (IPM), والتي تجمع بين المكافحة الميكانيكية والكيميائية والحيوية للحد من الانتشار السريع لهذه الافة.

الكلمات المفتاحية: *Dactylopius opuntiae*, حشرة غازية، التوزيع المكاني، الخرائط الحرارية، الإدارة المتكاملة للمكافحة (IPM).

Introduction

The family Dactylopiidae comprises a single genus Dactylopius, which includes 11 species of scale insects. These species represent some of the most economically damaging pests affecting prickly pear (*Opuntia ficus-indica*) globally. The species *Dactylopius opuntiae* (Cockerell, 1896) (Hemiptera: Dactylopiidae) is highly damaging [1, 2]. The phytophagous feeding behavior of adult females and nymphs targets the vital sap of the host, causing chlorophyll degradation that initially manifests as localized chlorotic zones [3]. These patches expand as pest populations grow, leading to cladode wilting, abscission and eventual plant death [1, 3, 4].

Dispersal occurs via wind currents, human activities and animal movements. Nymphs produce white waxy filaments that reduce their density, facilitating dispersal by wind between hosts [5]. Characterized by high host specificity *Dactylopius opuntiae* is represented by two biotypes, the stricta biotype, which strictly colonizes *Opuntia stricta*, and fails to sustain viable cohorts on *Opuntia ficus-indica* alongside limited development on *Opuntia stricta* [6]. Recently, this invasive insect has spread extensively across the Mediterranean basin including Palestine, Syria, Morocco, Algeria, and Tunisia, causing financial losses worth millions of dollars in management costs. The pest's resistance to standard mitigation is governed by a combination of high reproductive potential, rapid spread, and dense wax covering that effectively insulates the insect body from contact chemical pesticides [7, 8].

In Libya *D. opuntiae* was initially recorded in May 2024 in Al-Twaybia district [9, 10], it rapidly spread into adjacent territories (Zawiya, Abu Surrah, and Janzur), and distant sectors Al-Garabulli district, severely damaging O. *ficus-indica* [11]. This expansion was driven by climatic factors, such as elevated temperatures, low humidity, and seasonal wind velocities [12], and alongside a lack of timely control measures by relevant authorities. The present study aims to evaluate the distribution of *D. opuntiae* in Al-Jafara, establishes its morphological classification, determines regional infestation severity across local municipalities, assess its ecological impact pear, and propose an Integrated Pest Management (IPM) program.

Material and methods

1-Description of the study area: geographic and climatic characteristics of Al-Jafara:

The Al-Jafara region is located in northwestern Libya, it is an expansive coastal plain bounded by the Mediterranean Sea to the north and the Western Mountain to the south. The Al-Jafara region is an agricultural area covering 2,666 km^2, and comprising eight municipalities (Fig. 1). The region is dominated by a semi-arid Mediterranean climate, which is characterized by hot, dry summers and mild cold winters with limited seasonal rainfall. Average annual rainfall ranges between 200 and 400 millimeters [12, 13, 14]. While wind velocities are generally moderate, they adequately contribute to pest dispersal under conducive conditions, affecting pest distribution and host vegetation dynamics [15].

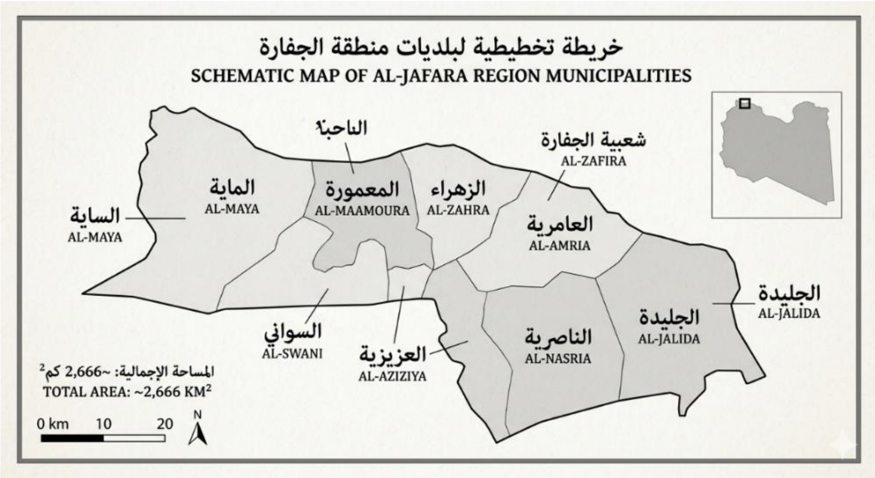


Figure (1): Geographic location of the study area mapped within Libya.

2-Data collection method and field surveying:

This study was conducted from September 2025 to June 2026, to identify the species and assess the distribution and infestation severity of the cochineal insect on prickly pear (*Opuntia ficus-indica*) in the Al-Jafara region. The fieldwork included visits to 22 localities across 8 municipalities within Al-Jafara (Table 1). Visual assessments categorized scale insect infestation into three tiers (mild, moderate, severe) based on colony density and cladode coverage. Given that prickly pear in Libya predominantly grows as border hedgerows along roads and farms, and to overcome logistical and private property constraints, a Systematic Linear Hedgerow Sampling approach was adopted. This strategy minimized logistical limitations and legal parameters associated with private land access. Adhering to the international benchmarks outlined in the *Hedgerow Survey Handbook* [16], the vegetative barriers were segmented into uniform spatial intervals ranging from 5 to 10 meters relative to total hedgerow length, thereby ensuring representative sampling and reducing sampling bias. This methodology is well-documented in scientific literature [16, 17, 18]. The highest abundance of prickly pear in the study area occurs along roadsides and between farms, making most of these populations accessible for study.

Table (1): Municipalities and sampled localities within the Al-Jafara region.

Municipality No.	Municipality Name	Area No.	Area Name	Longitude	Latitude
1	Al-Maamoura	1	Qargoza	12.8630°	32.7166°
		2	Eastern Al-Maamoura		
		3	Northern Al-Maamoura		
2	Al-Maya	4	Northern Al-Maya	12.9500°	32.7667°
		5	Al-Teena		
		6	Al-Twaybia		
3	Az-Zahra	7	Az-Zahra Center	12.8700°	32.6800°
		8	Southern Az-Zahra		
		9	Al-Barounia		
		10	Northern Az-Zahra		
4	Al-Amriya	11	Al-Rafeefia	**12.9463°**	**32.6841°**
		12	Al-Ameria Center		
		13	Western Al-Ameria		
5	Al-Nasria	14	Al-Zayat	**12.8736°**	**32.6328°**
		15	Western Al-Nasria		
6	Al-Azizia	16	Bir Al-Jadeed	13.0213°	32.5307°
		17	Al-Saadia		
7	Al-Swani	18	Al-Karimia	13.0700°	32.7100°
		19	Al-Toghar		
		20	Ghot Abu Saq		
		21	Awlad Issa		
8	Al-Jlaida	22	Northern Al-Jlaida	12.9238°	32.5539°

3-Quantification of infestation severity:

To calculate infestation severity and ensure representative field coverage, a proportionate systematic sampling approach was adopted. Depending on the abundance and density of prickly pear plants, 2 to 6 distinct locations per district, within each site, 3 to 6 plants were evaluated, and a vertical sample of 5 cladodes per plant (from bottom to top) was inspected to assess colony density and determine the infestation level. The collected data comprising the total number of inspected sites, and cladodes alongside the recorded colony counts were tabulated to compute the regional infestation severity using the McKinney (1923) formula [19]. This specific index constitutes a standard severity index in phytopathology, designated globally as the Severity Index (SI), or Disease Severity Index (DSI), and is standard in scale insect surveys (e.g., Bouharroud et al., 2018; FAO & ICARDA, 2022) [20, 21]. The equation is expressed as follows:

$$\mathbf{SI}= \frac{\sum(\boldsymbol{n_i} \times \boldsymbol{v_i})}{\boldsymbol{N} \times \boldsymbol{V}} \times \mathbf{100}$$

Definition of equation symbols:
SI = Infestation severity index (%).
ni = Number of cladodes in each infestation grade.
vi = Numerical value of the infestation grade (ranging from 0 to 5).
N = Total number of inspected cladodes.
V = Highest possible infestation grade (equal to 5 in this study).

4-Generation of the infestation Heat Map:

Field data regarding the distribution of the cochineal insect were collected across Al-Jafara region. Latitude and longitude parameters for the respective municipalities were retrieved from municipal surveying departments, where positions had been established via GPS surveying. These spatial frameworks were integrated with our collected data on infestation degrees and colony counts across Al-Jafara municipalities to calculate the mean infestation intensity was computed for each municipality. Geospatial analysis was subsequently conducted in QGIS software, converting the dataset into a vector point layer. Kernel Density Estimation (KDE) algorithm was implemented to yield distribution heatmaps. To capture a spatial distribution pattern of the insect population, the infestation grade was assigned as the weight field, complemented by a designated bandwidth of 2000 meters. Additionally, the raster resolution was configured to align with the specific geographical attributes of Al-Jafara.

5- Sample collection and insect taxonomic classification methods:

Insect specimens were manually isolated and collected from infested *O. ficus-indica* cladodes using fine tweezers and a soft-bristled brush (Figure 2: A, B) then placed the collected specimens into sterile plastic vials, preserved them in 70% ethyl alcohol (Figure 2: C), and transported to the laboratory for detailed examination. To facilitate morphological description via stereomicroscopy and light microscopy, the specimens underwent multiple rinses with 70% ethyl alcohol to ensure the removal of wax secretions, thereby enabling clear visualization and digital imaging of adult females along with their developmental stages (nymphs and eggs). Adult male was collected nocturnally by artificial light sources in high-infestation areas (specifically within the Al-Maamoura municipality), preserved them in 70% ethyl alcohol, and microscopically recorded. For anatomical characterization, adult female samples were rinsed with distilled water to eliminate residual alcohol, transferred to a reaction flask, and immersed in a freshly prepared 10% potassium hydroxide (KOH) solution (Figure 2: D, E). To expedite the clearing process, selected specimens were heated on a hot plate at a moderate temperature for 15 minutes (Figure 2: F), and subsequently maintained in the KOH solution for 24 hours. Alternatively, other specimens were sustained in the KOH solution at room temperature for 24 to 48 hours without thermal treatment to fully dissolve internal viscera and remove the intense crimson pigmentation while preserving delicate external structures (Figure 2: G), if internal organs remained incompletely digested, we made a micro-puncture on the lateral edge of the female's using a sterile needle (Figure 2: I), followed by an additional 24-hour incubation period. Following clearing, we rinsed the specimens thoroughly with distilled water (Figure 2: H), and dehydrated them through an ascending series of ethyl alcohol (Figure 2: J). The cleared tissues were stained using iodine stain, and permanently slide-mounted in Canada balsam. Finally, the prepared slides were analyzed under a light microscope to diagnose and photograph diagnostic morphological characters, specifically the antennae, legs, spiracles, setae, and the morphology and distribution of wide-rimmed spiracles, setae, and the morphology and distribution of wide-rimmed pores (WRP).

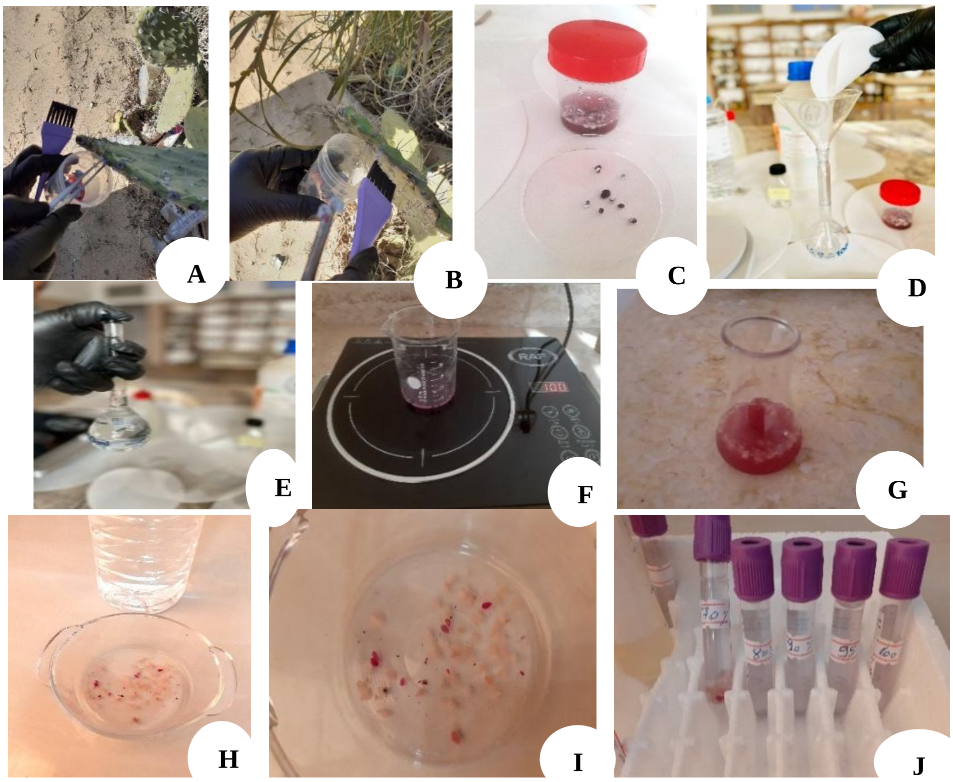


Figure (2): Methodological steps for sample collection, preservation, and potassium hydroxide (KOH) processing: A, B: Manual collection of specimens from cladodes; C: preservation of samples in 70% ethyl alcohol; D, E: Preparation of 10% KOH solution; F: Thermal treatment of selected samples in KOH solution; G: Room-temperature incubation of samples in KOH without heating; H: Sequential rinsing of KOH-treated specimens with distilled water; I: Make micro-puncture in females J: dehydration of specimens through a graded ascending series of ethyl alcohol.

Result:

1-Taxonomic status and diagnostic validation of *Dactylopius opuntiae* in Al-Jafara:

Based on microscopic evaluation and field characteristics, the cochineal insect occurring in the Al-Jafara region was identified as *Dactylopius opuntiae* (Cockerell, 1896), belonging to the family Dactylopiidae, Order Hemiptera, a species native to Mexico. It was first described in 1896 by the scientist Cockerell, *D. opuntiae* is documented as one of the most destructive pests affecting Opuntia species, particularly *O. ficus-indica*. Field observations confirmed that it is a soft- bodied, oval-shaped unsegmented insect that aggregates in dense colonies on cactus cladodes, completely enveloped by a thick, cottony, white waxy secretion, Multiple life stages were successfully collected and identified, including wingless adult females, eggs, mobile female nymphs, wingless male nymphs, and winged adult males. The specimens were taxonomically keyed according to De Lotto (1974), and Guerra (1992) [22, 23], confirmed the identification through key diagnostic features such as the morphology of conical spines and the specific arrangement of wide-rimmed pores (WRP) associated with tubular ducts. Morphological and anatomical details compiled from local populations are structured in Figures (3,4,5).

Morphological characterization of the investigated adult male specimens:

The adult male has a minute body clearly differentiated into a head, thorax, and abdomen, display a slender, appearing light red to yellowish-brown (Figure 3: A). They possess long filiform 10-segmented antennae covered with sensory setae (Figure 3: B). Three pairs of elongated walking legs (Figure 3: C), a single pair of fragile hyaline forewings (Figure 3: D), and a pair of long, slender anal filaments projecting posteriorly (Figure 3: E).

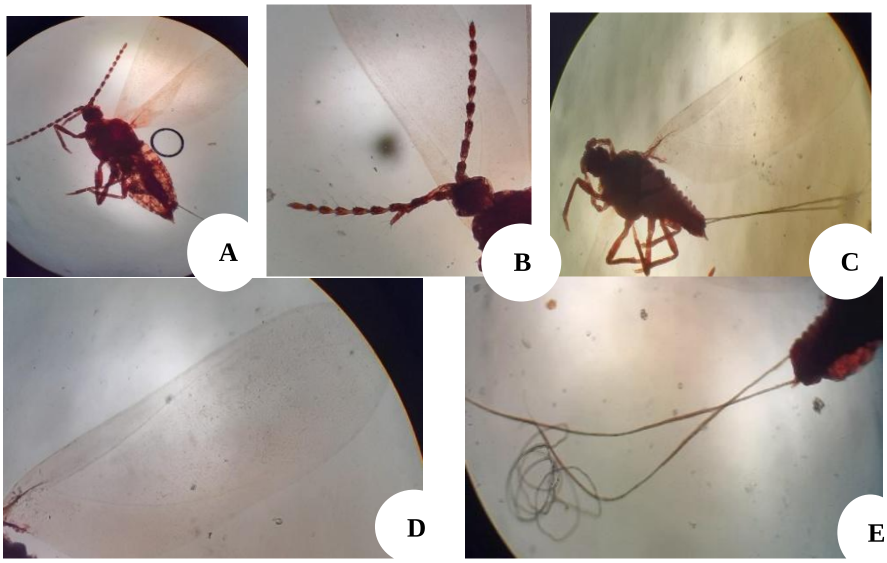


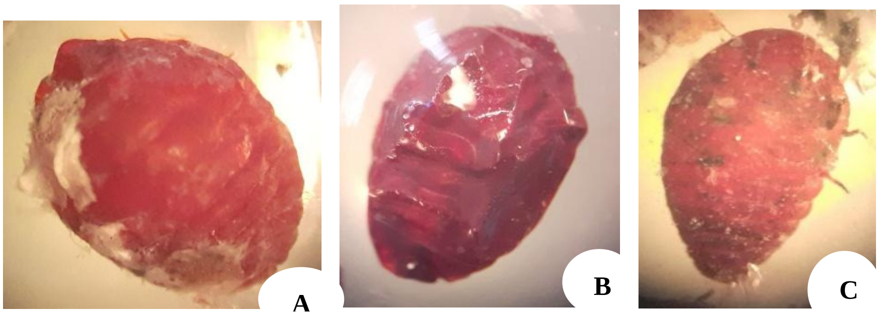
Figure (3): shows the morphological characteristics of adult males of *D. opuntiae* collected from the study areas: A: Body morphology and segmentation; B: Antennal morphology; C: Structure of ambulatory legs; D: Wing shape; E: Abdominal appendages.

Morphological characteristics of the investigated adult female:

Living adult females are broadly oval, dorsally convex, and wingless. Under their dense, white cottony wax covering, the body color is dark purple (Crimson) (Figure 4: A, B, C, D). Antennae are short and rudimentary with 7 segments (Figure 5: E, F), and the piercing sucking mouthparts consist of a cone shaped rostrum with four fine stylets (Figure 5: G, H). There are three pairs of short, stout legs (Figure 5: I, J, K).

Slide mounted specimens confirmed the identity of *D. opuntiae*. The derm features thick, wide-based conical setae that are dense on the final three abdominal segments (Figure 5: L, N), while elongated truncate setae are scattered across the dorsum (Figure 5: M, N). Dermal pore distribution is consistent with descriptions of De Lotto (1974) and Guerra (1992). On the dorsum, Wide-Rimmed Pores (WRP), each associated with a tubular duct (Figure 5: O, P, S), occur in low numbers on the anterior and median areas. However, these WRP clusters are mainly distributed on both the dorsal and ventral margins of the last three abdominal segments (Figure 5: Q), forming distinct marginal bands. Flat, Narrow-Rimmed Pores (NRP) are abundant and packed mainly on the ventral mid-area of these same posterior segments (Figure 5: R, S), with fewer pores on the preceding segments.

The anterior and posterior spiracles are large, each with developed, rough edged sclerotized operculum (Figure 5: T, U). This phenotypic identification agrees with records from Tunisia, Algeria, Morocco, and Mauritania, confirming *D. opuntiae* as the main cause of wild of cochineal outbreaks in North Africa. This also supports recent findings by the Bioresearch Center in Tripoli (Abukraa et al., 2026), showing that WRP analysis is reliable for separating closely related Dactylopius species.



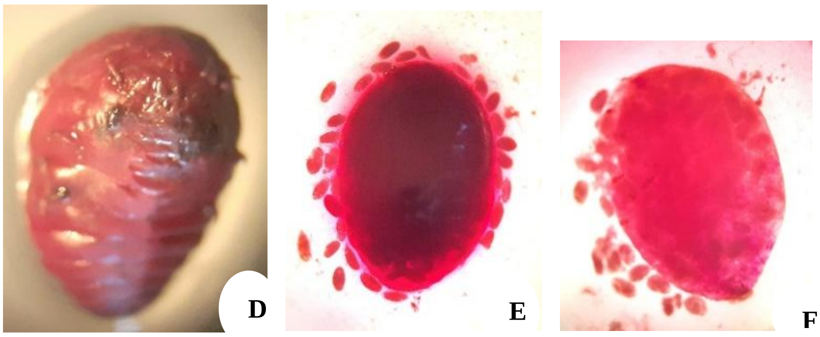
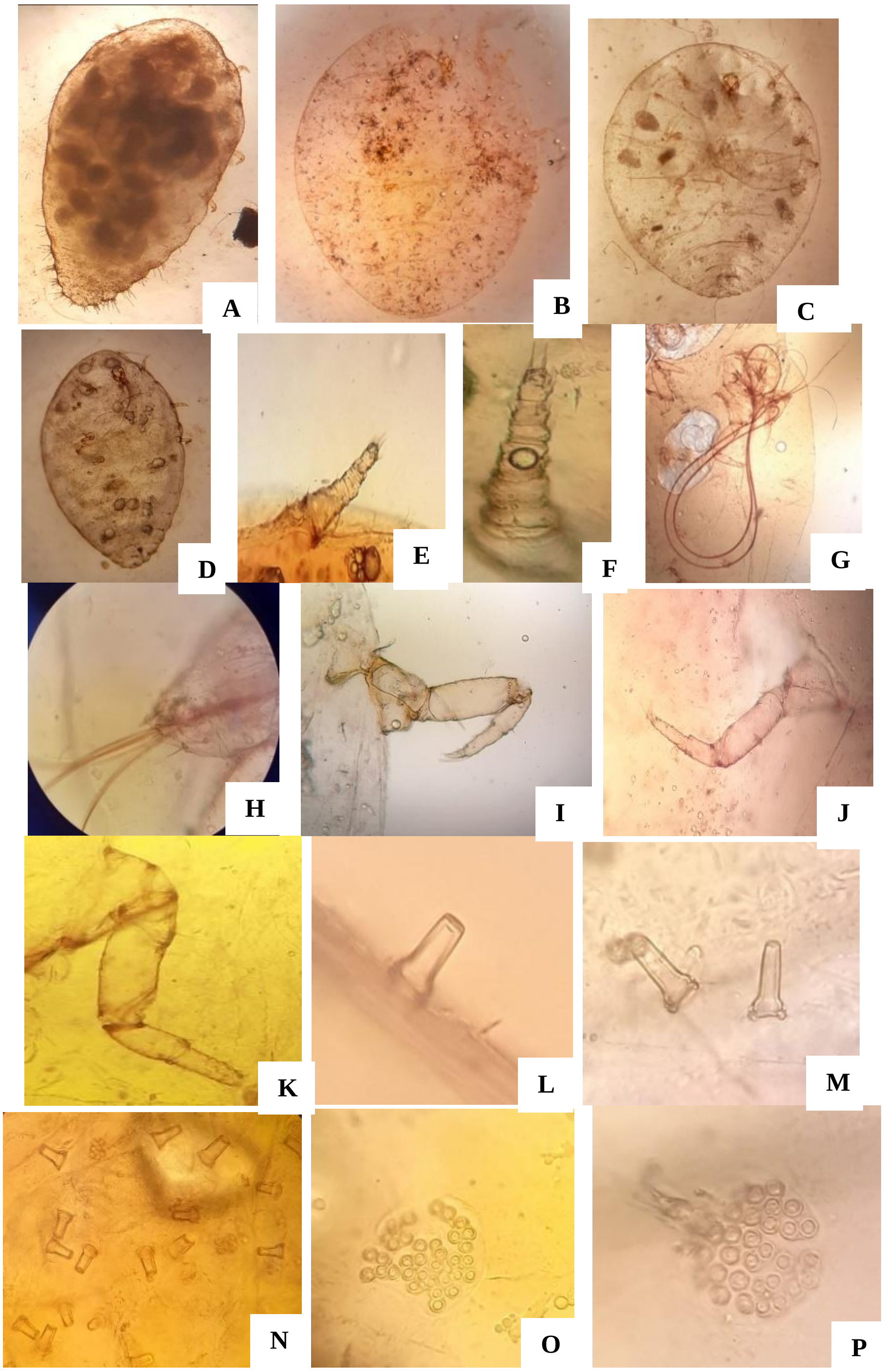


Figure (4): Pre-clearing morphological structure of adult females of *D. opuntiae* collected from the study area; A, B: Dorsal view of the adult female body; C, D: Ventral view of the adult female body; E, F: Gravid female body packed with eggs.



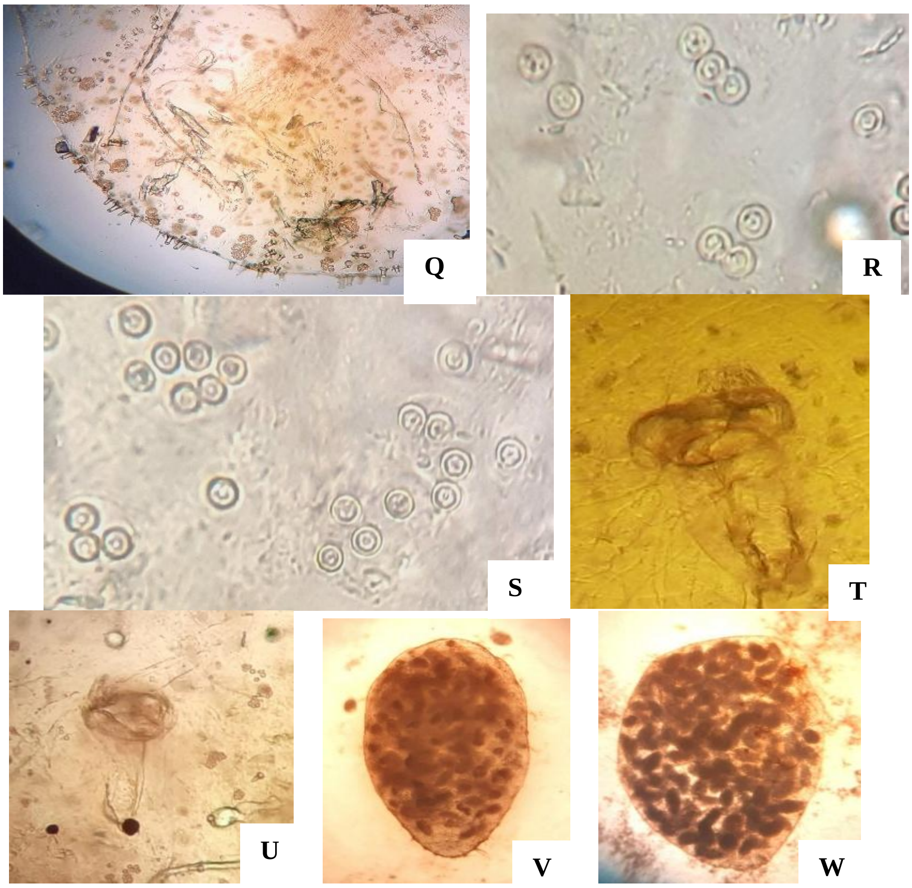
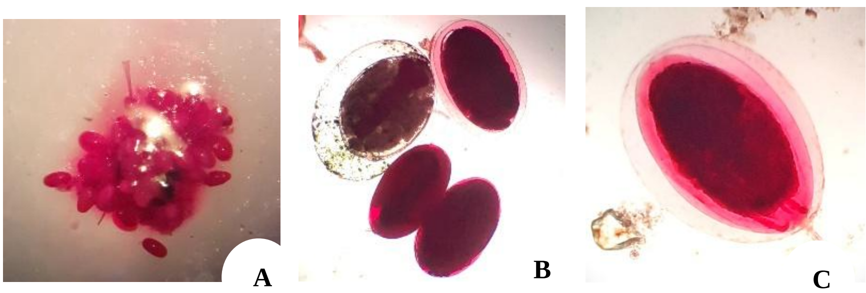


Figure (5): Post-clearing morphological structures of adult females of *D. opuntiae* treated with KOH solution: A, B: Dorsal view; C, D: Ventral view highlighting the cephalic region; E, F:Morphology of antennae (consisting of 7-segmented); G: Morphology of the sucking mouthparts (Rostrum); H: Detail of the piercing stylets; I: Prothoracic leg; J: Mesothoracic leg; K: Metathoracic leg; L: The Wide/Stout Truncate Setae; M: The Thick/Elongated Truncate Setae; N: Density of two type of Setae; O, P: WRP associated with a tubular duct; Q: High density and distribution of pores on the terminal three abdominal segments; R: NRP; S: WRP & NRP; T, U: Spiracles (Breathing pores); V, W:Gravid female body packed with eggs.

Characterization of the collected life stages of *D. opuntiae*:

The collected, examined, and photographed life stages of *D. opuntiae*, the ovicidal stage manifested as both isolated and clustered eggs (Figure 6: A, B) with mature eggs harboring fully formed first-instar nymphs of both sexes (Figure 6: C). Field populations also contained second-instar female (Figure 6: D, E), and male nymphs (Figure 6: G, H), these individuals function as highly active, mobile (Crawlers) that are highly susceptible to passive transport by active wind currents. The sampling also yielded third-instar female nymphs (Figure 6: F), and adult males collected directly from prickly pear cladodes alongside the aforementioned stages (Figure 6: I). A size dimorphism was noted among the adult males, those retrieved directly from the host plants were conspicuously smaller than the specimens intercepted at artificial light sources deployed adjacent to households in the highly endemic zones. Residual fragments of male cocoons on the cladode (Figure 6: J, k)**.**



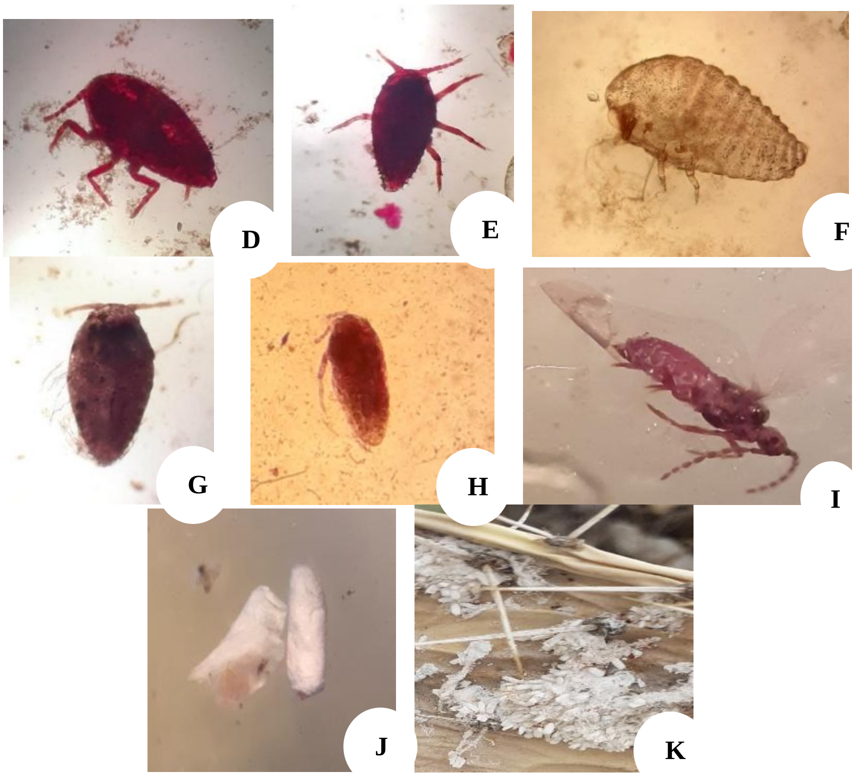
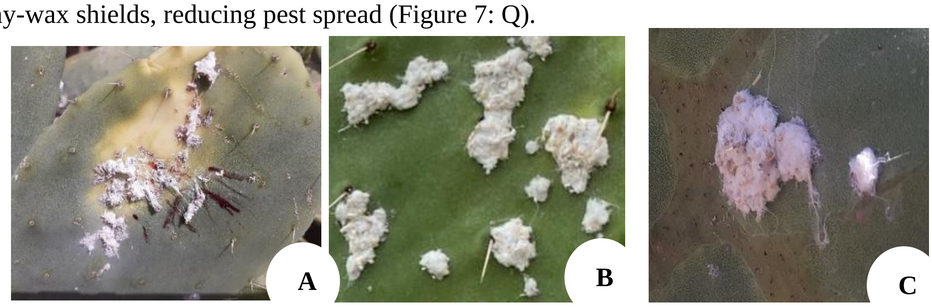


Figure (6): developmental stages of *D. opuntiae;* A: Clustered insect eggs; B: Solitary eggs; C: First-instar nymph; D, E: Second-instar female; F: Third-instar female; G, H: First-instar male; I: Flighted adult male; J: Pupal cocoon; K: Residual fragments of male cocoons.

3- Field observations and impact of abiotic factors on *D. opuntiae* populations:

Field investigations revealed key ecological observations of *D. opuntiae*. Crushing the insect on prickly pear cladodes yields a crimson body fluid (Figure 7: A). The adult females generate an abundant, dense, white cottony-waxy matrix that entirely envelops the sedentary colonies (Figure 7: B, C). These colonies are widely and sparsely distributed along the cladodes, appearing as prominent, scattered white spots (Figure 7: D, E). This wild serious pest species causes extensive damage to host plants (Figure 7: F), inducing broad yellow chlorotic spots that lead to cladode wilting and abscission (Figure 7: G, H, I). Infestations preferentially occur on shaded cladodes protected from direct sunlight (Figure 7: J, K). *D. opuntiae* exhibited high host specificity, primarily restricted to *O. ficus-indica*. Symptomless or extremely mild infestations were observed on *Opuntia imbricata* restricted to a single locality within Oargoza (Figure 7: L, M), the vast majority of *O. imbricata* individuals remained uninfested (Figure 7: N)., despite being sympatric with severely infested *O. ficus-indica* stands. Field assessments during two-month period of strong dusty winds (December 2025 to January 2026) revealed high mortality rates, the insect colonies collapsed, leaving behind dry, yellow necrotic scars, which correlated with a marked arrest in population growth (Figure 7: O, P). This was followed by torrential rainfall that mechanically partially or completely removed the cottony-wax shields, reducing pest spread (Figure 7: Q).



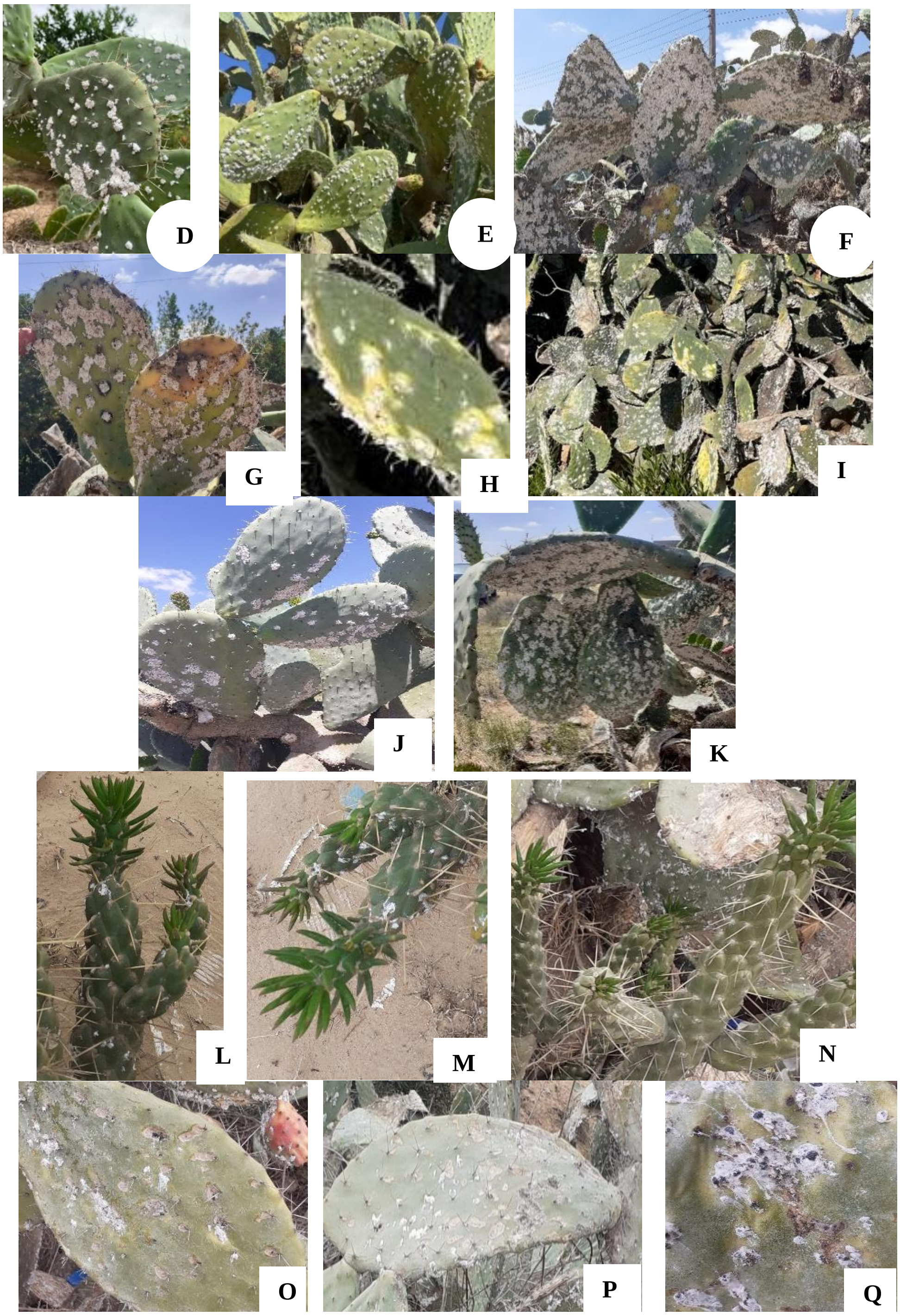


Figure (7): Distinctive field observations of species *D. opuntiae;* A: Exudation of characteristic crimson pigment upon crushing the insect; B, C: Abundant white waxy secretions covering insect colonies; D, E: The distribution of insect colonies on Opuntia cladodes; F: Hyper-severe infestation on *O. ficus-indica* plants; G, H, I: Severe chlorosis and wilting of the host plant induced by high infestation; J, K: Insect micro-habitat preference for shaded cladode surfaces shielded from direct sunlight; L, M: Mild infestation symptoms on *Opuntia imbricata*; N: Uninfested stands of *O. imbricata* exhibiting resistance within heavily infested zones; O, P: Insect mortality induced by dust-laden high winds; Q: Elimination of the protective waxy coating from colonies due to heavy rainfall.

4- Infestation subtleties of *D. opuntiae* across Al-Jafara municipalities:

Field survey results revealed a distinct variation in *D. opuntiae* infestation severity on *O. ficus-indica* across Al-Jafara municipalities (Table 2). The intensity of the infestation levels varied widely, ranging from high infestation levels to minor, superficial occurrences. Quantitatively the highest infestation rates were recorded in Al-Maamoura municipality at 86.4%, followed closely by Al-Maya at 80.9%. An-Nasriya and Az-Zahra municipalities exhibited infestation rates of 67.4% and 61.1% respectively. Moderate infestation levels were observed in AL-Amriya (54.5%) and Al-Swani (54.4%). Conversely, Al-Jlaida municipality recorded a relatively low infestation rate of 27%. While the lowest prevalence was documented in Al-Azizya at only 5% (Table 3).

Table (2): infestation severity across Al-Jafara municipalities and corresponding calculation datasets:

Municipality	Study Locality	Inspected Sites (N)	Inspected Plants (N)	Total Cladodes (N)	Colonies per Cladode	Infestation Severity (%)	Mean Severity per Municipality (%)
Al-Maamoura	Qargouza	4	6	120	>50	96.0	86.4
	Eastern Al-Maamoura	3	6	90	>50	85.1	
	Northern Al-Maamoura	3	4	60	>50	78.0	
Al-Maya	Al-Tuwaibiya	3	4	60	>50	95.3	80.9
	Al-Tina	2	6	75	>50	77.3	
	Northern Al-Maya	3	6	90	>50	70.0	
Al-Zahra	Al-Zahra Center	3	3	45	20–50	62.0	61.1
	Southern Al-Zahra	4	4	80	>50	55.7	
	Al-Barouniya	4	4	80	>50	65.5	
	Northern Al-Zahra	3	4	60	>50	61.3	
Al-Nasriya	Al-Zayat	3	4	60	20–50	69.0	67.4
	Western Al-Nasriya	3	5	75	20–50	65.8	
Al-Amriya	Al-Rafifiya	6	5	150	20–50	40.0	54.5
	Al-Amriya Center	4	6	120	>50	71.6	
	Western Al-Amriya	5	6	150	20–50	51.8	
Al-Swani	Al-Karimiya	3	5	75	20–50	52.6	54.4
	Al-Toghar	4	6	120	20–50	65.8	
	Ghot Abu Saq	5	6	150	20–50	46.3	
	Awlad Issa	6	6	180	>50	52.7	
Al-Aziziya	Bir Al-Jadid	7	6	210	0	0.0	5.0
	Al-Saadiya	5	6	150	1–10	10.0	
Al-Jalida	Northern Al-Jalida	2	4	40	1–10	27.0	27.0

Note: Infestation categories and plant conditions were removed from the table to reduce width. Sites with > 50 colonies per cladode were classified as severe infestation and typically showed chlorotic and wilted plants. Sites with 20 – 50 colonies per cladode were classified as moderate to severe infestation and generally exhibited early wilting symptoms. Sites with 1 – 10 colonies per cladode were classified as light infestation with healthy plants, whereas sites with zero colonies per cladode were considered uninfested and plants remained healthy. A standardized total of 5 cladodes per plant were systematically inspected across all surveyed sites.

5- GIS-Based spatial analysis of *D. opuntiae* infestation in Al-Jafara municipalities:

Using Geographic Information System (GIS) spatial heat maps were constructed based on mean municipality-level data to evaluate *D. opuntiae* infestation severity in Al-Jafara. The heat map results indicated that infestation severity was highest in the municipalities of Al-Maamoura and Al-Maya, whereas it decreased in Al-Aziziyah and Al-Jalida. Moreover, the heat maps demonstrated that infestation intensity peaks in the northwestern areas and gradually declined toward the south and southeast. This pattern suggests a potential influence of environmental factors and wind directions, which facilitated the extensive spread in the highly adjacent northwestern regions.

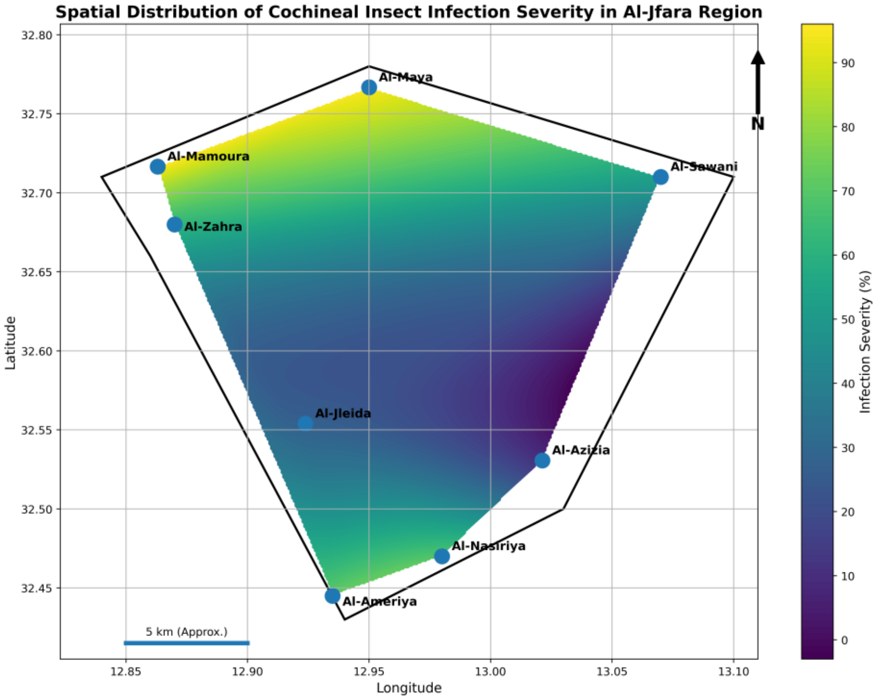


Figure (8): Heat map showing the spatial distribution and severity of *D. opuntiae* infestation across the municipalities of the Al-Jafara region, resultant from mean infestation index values recorded during the 2026 field survey.

Discussion

1- Taxonomic status and diagnostic validation of *D. opuntiae* in Al-Jafara:

Microscopic examination confirmed that all specimens collected from Al-Jafara region belong to *D. opuntiae*. This taxonomic consensus was achieved via specific diagnostic landmarks, primarily the density and distribution pattern of conical setae, alongside the localized arrangement of wide-rimmed pores (WRP) coupled with tubular ducts, these structures display conformity with the taxonomic studies of Meyers (2004), and Rodriguez & Llanderal (2012) [24, 25]. Given the high morphological similarity among Dactylopius species, the detection of WRPs serves as a reliable tool for species differentiation, as cuticular micro-characters are highly dependable metrics in scale insect taxonomy [26]. Geographically this identification aligns with previous reports from adjacent Maghreb countries Tunisia, Algeria, Mauritania, and Morocco, which documented *D. opuntiae* as the invasive damaging agent. Additionally, our taxonomic conclusion corroborates the recent findings of [11] from the Biotechnology Research Center in Tripoli, which identified the species using comparable morphological parameters.

2- Epidemiological modeling and multifactorial analysis of *D. opuntiae* expansion:

Field survey results in Al-Jafara region indicate that *D. opuntiae* infestation has transitioned from isolated epicenters into a widespread infestation, peaking above 80% in Al-Maya and Al-Maamoura. A comparable rapid expansion was reported in Morocco, culminating in the rapid destruction of extensive Opuntia plantations [27]. This widespread prevalence correlates directly with host plant density (*O. ficus-indica*), zones with high host abundance exhibited the highest infestation severity, validating that host density is a critical determinant of distribution patterns [28, 3]. Exhibited extremely negligible, non-damaging insect counts. The association with host density is clear, municipalities with extensive, continuous cultivation of traditional prickly pear hedges recorded severe population increases, whereas regions like Al-Azizia, where the host plant is scarce, showed minimal pest establishment [26].

The rapid spread was likely promoted by Al-Jafara climate characterized by high temperatures and low relative humidity which favors *D. opuntiae* reproduction. This environmental advantage was compounded by a lack of Integrated Pest Management (IPM) practices and the absence of native natural enemies capable of suppressing population surges [29]. High infestation zones suffered severe plant damage, including widespread chlorosis, wilting and desiccation due to intensive sap-depletion aligning with established literature [3]. Cartographically, spatial kernel density heatmaps identified the northwestern sectors as the primary epicenters of the invasion, showing a reduction toward southern areas and southeast. This spatial gradient suggests the combined influence of prevailing wind directions and human activities, such as the movement of farmers and the transport of fruit crates between field and local markets. Utilizing GIS-based heatmaps successfully clarified these spatial patterns, identifying high risk zones to support future monitoring and management strategies.

3- Management framework for Integrated Pest Management (IPM):

The findings of this study show an immediate need for Integrated Pest Management programs to control *D. opuntiaein* in Libya [27, 30, 31]. Field observations in the study areas revealed variability in infestation levels, reflecting differences in farmer awareness and farm management practices. The absence of an effective early warning system contributed to delayed detection and increased pest spread, this supports the need for a structured (IPM) program starting with awareness, followed by monitoring, mechanical, biological, and chemical control strategies Table 3 [32].

This study represents one of the first investigations to examine *D. opuntiaein* in the Libyan ecosystem, providing baseline data on its identity and distribution. Linking standard morphology with WRP analysis reduces diagnostic errors and improves taxonomic accuracy in regional surveys.

Table (3): Proposed IPM strategy in Libya:

phase	Component	Actions	Objective	Notes
1	Awareness	Training farmers, campaigns	Early detection	Critical step
2	Monitoring	Regular inspection	Detect early	Depends on awareness
3	Containment	Isolation, removal	Limit spread	Immediate action
4	Mechanical	Removal, cleaning	Reduce density	Low cost
5	Biological	Predators	Natural control	Needs study
6	Resistance	Resistant varieties	Sustainability	Long term
7	Chemical	Selective pesticides	Control severe cases	Limited use
8	Evaluation	Monitoring results	Improve strategy	Continuous

Conclusion

This study confirms that the cochineal insect Dactylopius opuntiae has become a very serious pest of the common prickly pear plant in Libya, species (Opuntia ficus-indica). This pest has spread widely in the western Libyan coast and has had clear negative environmental and agricultural impacts on the prickly pear plant. It also proved the effectiveness of the pore clusters technique (WRP) in phenotypic classification, with the need to support it with modern techniques. The results highlight the importance of rapid intervention through integrated management programs to reduce the spread of this pest and protect agricultural resources in the region.

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Authors contributions

Najat M. Al-Ghatmi: Collected the samples, calculated the infestation across the Al-Maya, Al-Maamoura, Al-Zahra, Al-Swani, and Al-Amriya Municipality, prepared, examined, identified, and photographed the specimens, and Writing Original Draft. Amhimmid M. Alkeesh: Calculated the infestation of Al-Nasria and Al-Jalida Municipality. Moudah J. Eisay: Collected the male insect samples. Malak N. Al Ferjani: Calculated the infestation of Al-Aziziya Municipality.

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Data availability: The data generated in this study are available within the publication.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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